Radiative Transfer Modeling for CoBOP

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LONG-TERM GOAL

The overall goal of this work is to take oceanic radiative transfer theory into a new domain: shallow waters with variable bottom optical properties and inherently three-dimensional light fields.

OBJECTIVES

Currently available optical models for bottom boundaries invariably assume that the bottom is a Lambertian reflecting surface—a surface whose reflected radiance appears the same from all viewing directions. The first objective of this year's work was to quantify the extent to which non-Lambertian bottoms can affect upwelling radiances as would be detected by in-water or above-water sensors. Many studies of marine light fields also assume the water and bottom optical properties to be horizontally homogeneous, which is not the case in shallow waters with patchy bottoms. The second objective this year was to quantify when a 1-D (depth dependence only) optical model is sufficient, and when a 3-D model must be used.

APPROACH

The Hydrolight 4.0 radiative transfer model (http://www.sequoiasci.com/Hydrolight.html; see also Mobley, 1998) allows for non-Lambertian bottom boundaries. However, because of the lack of measured Bi-directional Reflectance Distribution Functions (BRDFs; Mobley and Mazel, 1999) for actual ocean bottom materials, Hydrolight's mathematical capability had not been previously exploited. This year, non-Lambertian BRDFs were used in Hydrolight to simulate the effects of horizontally uniform but non-Lambertian bottoms such as seagrass canopies on in-water and water-leaving radiances.

The Hydrolight model requires the water and the surface and bottom boundaries to be horizontally homogeneous; Hydrolight is therefore not applicable to shallow waters with spatially variable bottom boundaries. To simulate inherently 3-D light fields due to the effects of spatially variable bottom reflectances, Monte Carlo models must be developed.

WORK COMPLETED

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I participated in the CoBOP field experiment during May and June 1999 at Lee Stocking Island, Bahamas. My work there centered on providing on-site radiative transfer simulations.

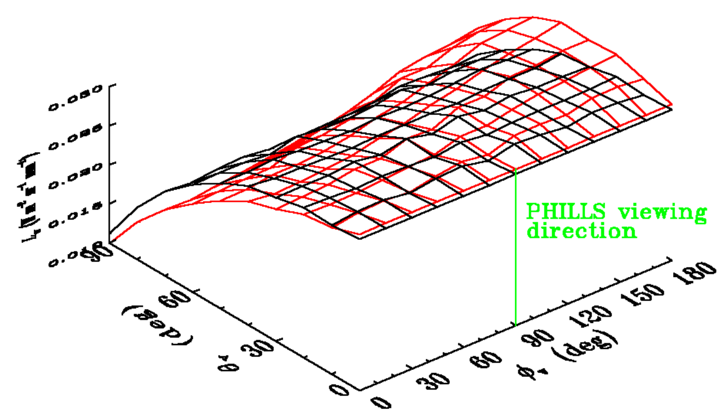
In this year's study, analytical models for non-Lambertian BRDFs were used to simulate radiances for situations of interest to the underwater Fluorescence Imaging Laser Line Scanner (FILLS) and the airborne Portable Hyperspectral Imaging Low-Light Spectrometer (PHILLS) systems, both of which play a major role in the CoBOP field programs. Analytical BRDFs developed for terrestrial plant canopies were used a proxies for seagrass BRDFs, which are not being measured directly in the CoBOP field experiments.

A Backward Monte Carlo model was developed to simulate 3-D radiance distributions caused by spatially variable bottom reflectances (such as patchy sand and seagrass bottoms). This model allows the user to specify an arbitrary spatial pattern of bottom BRDFs (which can be non-Lambertian) as well as sensor location, viewing direction, and field of view. This model was used for preliminary studies of 3-D light fields in shallow waters.

In addition to the work explicitly described here, I published or co-authored seven papers that contribute to the overall goals of CoBOP or to other Navy needs (Lee *et al*., 1999; Mobley, 1999a; McCormick and Mobley, 1999; Ohlmann, Siegel, and Mobley, 1999; Stephany *et al*., 1999; Stramska *et al*., 1999; Tyrrell, Holligan, and Mobley, 1999). Papers also were presented at the Ocean Optics XIV and ASLO Aquatic Sciences meetings (Mobley, 1998 and 1999b).

RESULTS

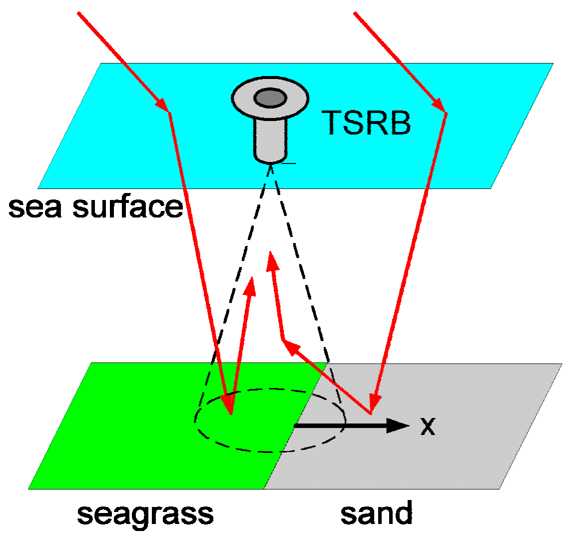
Figure 1 shows an example of a Hydrolight simulation of the water-leaving radiance L_w (the quantity of interest to the PHILLS sensor) for Lambertian and non-Lambertian bottoms *having the same irradiance reflectance R.* The non-Lambertian bottom used in this simulation was a BRDF of a wheat field, which was used as a proxy for a seagrass BRDF, the form of which is unknown. The water-column optical properties were taken from measured values at the CoBOP site; the water depth was 6 m. θ_v and ϕ_v are the polar and azimuthal viewing directions, respectively. The nadir viewing direction, which is the center of the PHILLS scan, is shown in green. The sun was located at $(\theta_v, \phi_v) = (60°,180°)$.



1. Comparison of water-leaving radiances for Lambertian (black mesh) and non-Lambertian (red mesh) bottoms having the same irradiance reflectances..

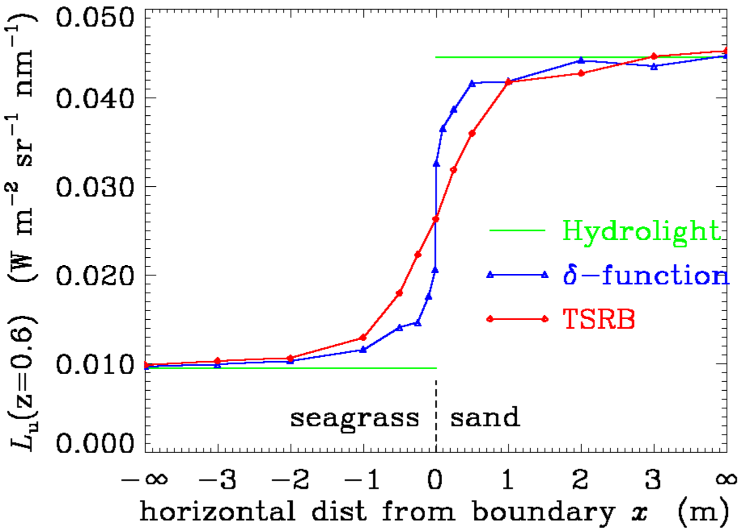
Simulations like those of Fig. 1 show that the different *angular* bottom reflectance patterns do not make much difference in the signals received by the PHILLS sensor. However, Lambertian and non-Lambertian bottoms can have much different irradiance reflectances R. Thus the main effect of a non-Lambertian bottom is its effect on the overall *magnitude* of the upwelling radiance. *The assumption of a Lambertian bottom is often acceptable if the irradiance reflectance is correct.* Additional results are given in Mobley (1999b).

Figure 2 shows a situation for which the light field is inherently 3-dimensional. The shallow bottom consists of a half-plane of seagrass ($x < 0$) and a half-plane of sand ($x > 0$), which have much different bottom irradiance reflectances. A Tethered Spectro-Radiometer Buoy (TSRB) is measuring the upwelling radiance at a depth of 0.6 m below the surface. The nominal field of view of the radiometer is represented by the dotted lines. As the TSRB is towed across the grass-sand boundary, we go from a 1-D grass domain to a 1-D sand domain, with a 3-D optical mixture of both near the boundary, as represented by the light rays (red), which are reflecting from both bottom types.



2. Example of an inhomogeneous bottom, which gives rise to a 3-dimensional light field.

Figure 3 shows three simulations of the upwelling radiance L_u at the TSRB for the geometry of Fig. 2. The green lines in the figure show the Hydrolight-computed values for infinite grass and infinite sand bottoms for comparison. The blue line shows L_u as computed by the 3-D Backward Monte Carlo model when simulating an idealized sensor with perfect collimation (a delta-function field of view). The red line shows L_u computed using the actual TSRB angular response function (a nominal 9° HWHM field of view in water). Values of water optical properties and bottom reflectances typical of the CoBOP site were used in the simulations.



3. Simulations of the upwelling radiance showing the transition from 1-D to 3-D light fields near a boundary between grass and sand bottoms.

In Fig. 3, the difference between the Hydrolight and the delta-function curves shows the inherent 3-D effects near the boundary. The difference between the delta-function and the TSRB curves shows the additional effects of the finite field of view of the TSRB sensor. For the conditions of this particular simulation (water depth and optical properties, bottom types, sensor geometry, etc.), L_u at the TSRB is essentially the same as the 1-D (Hydrolight) value for distances of more than 2 m from the boundary. Simulations of 3-D light fields are just beginning and will be a major focus of next year's work.

IMPACT/APPLICATION

Inverse models are being developed by other ONR investigators to retrieve bottom depths and bottom classification information from hyperspectral ocean color sensors such as PHILLS. Those retrieval algorithms generally assume the bottom to be a Lambertian reflector. Radiative transfer simulations like those in the present work allow the proposed inversion algorithms to be evaluated for non-Lambertian bottom boundaries.

The 3-D vs. 1-D simulations allow a determination of when a computationally efficient 1-D model like Hydrolight can be used to simulate the ocean optical environment, and when a much more expensive 3-D Monte Carlo model must be run. The 3-D Monte Carlo model developed here also allows for simulations of particular sensor geometries (such as sensor angular response), which cannot be exactly simulated in models such as Hydrolight.

Three-dimensional radiative transfer modeling like that mentioned above is fundamental to understanding the signals received by the FILLS sensor, or by the related EOID sensor, when operated in daylight, elastic-scattering mode.

TRANSITIONS

1. Simulation results for non-Lambertian bottoms have been requested by Dr. Curtiss Davis of NRL Code 7212 for use in evaluating the performance of the PHILLS sensor.

RELATED PROJECTS

Measurements of BRDFs for various bottom types are being made by K. Voss; these BRDFs will be incorporated into the simulations as they become available. Measurements of water and bottom optical properties and associated light fields are being made by various investigators in the CoBOP program. Their data, when available, will be used to validate the 3-D Backward Monte Carlo I have developed. This Monte Carlo model, in turn, will be used in the synthesis of the optical closure experiment planned for the 2000 field experiment.

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